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Locating North Atlantic Right Whales (Eubalaena Glacialis) in the Bay of Fundy using Multiple Sonobuoys

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Contract Number W7707-9-7146

Defence R&D Canada

Contractor Report
DREA CR 2001-062
September 2001

National Defence Défense nationale

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LOCATING NORTH ATLANTIC RIGHT WHALES *(EUBALAENA GLACIALIS)* IN THE BAY OF FUNDY USING MULTIPLE SONOBUOYS

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Approved by

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Scientific Authority

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Abstract

In July 1999, a 160 km^2 array of 17 sonobuoys was deployed in the Grand Manan Basin area of the Bay of Fundy within the designated North Atlantic right whale conservation area. The objectives of this study were to determine the accuracy of locating right whales based on their sounds; to estimate source levels of these sounds; and to determine sound travel distances. Two general types of sounds were identified, typical tonal vocalisations and broad band 0.2 s duration 'gunshots'. Tonal vocalisations occurred at 0.9 min^{-1} and their locations were determined to within 1.92 km^2 (±2.65 km^2 SD) on average. Gunshot type sounds were detected at 0.3 min^{-1} and determined to within 4.89 km^2 (±4.80 km^2 SD) on average. Right whale sound source levels were estimated to be 142-179 dB *re* 1 $\mu Pa^2/Hz$ @ 1 m. Source levels appeared to be dependent on frequency. The mean distance to sounds detected was 9.92 km. The average signal-to-noise ratio was 13.64 dB, with a minimum of 5 dB. Signal-to-noise did not depend on frequency or distance. Further research is continuing to investigate methods of automatically detecting right whale sounds in order to improve the possibility of implementing a real-time whale tracking system.

Résumé

En juillet 1999, un réseau de 17 bouées acoustiques était déployé sur une superficie de 160 km^2 dans la région du bassin de Grand Manan de la baie de Fundy, à l'intérieur de la zone désignée pour la protection de la baleine noire de l'Atlantique Nord. Les objectifs de cette étude consistaient à déterminer l'exactitude de la localisation de ces baleines d'après leurs sons, à estimer les niveaux d'émission de ces sons et à déterminer les distances de propagation des sons. Deux types de sons courants ont été définis: les vocalisations tonales types et les «coups isolés» large bande d'une durée de 0,2 s. Les vocalisations tonales se produisaient une fréquence de 0,9 min^{-1} et leurs emplacements d'émission étaient déterminés en moyenne au 1,92 km^2 près (écart-type de ±2,65 km^2). Les sons semblables à des coups isolés étaient détectés à une fréquence de 0,3 min^{-1} et déterminés en moyenne aux 4,89 km^2 près (écart-type de ±4,80 km^2). Les niveaux d'émission de la baleine noire étaient estimés de 142 à 179 dB *re* 1 $\mu Pa^2/Hz$ @ 1 m. Les niveaux d'émission semblaient être liés à la fréquence. La distance moyenne à laquelle étaient détectés les sons était de 9,92 km. Le rapport signal/bruit moyen était de 13,64 dB, avec un minimum de 5 dB. Ce rapport n'était lié ni à la fréquence ni à la distance. Des recherches approfondies examinent des méthodes de détection automatique des sons de la baleine noire afin de faciliter la mise en place d'un système de repérage en temps réel des baleines.

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Executive summary

In recent years, the Canadian navy has become increasingly concerned with the potential impacts of naval exercises, such as Low Frequency Active (LFA) sonar or ship transit, in or near sensitive habitats of endangered whale species. One way to minimize impacts is to determine where the whales are at all times during such exercises.

One suggestion for accomplishing the above goals is to use whale sounds to automatically locate them by computer in real time. This information can then be relayed to ships to provide advance warning that whales are present in the area. On 29 July 1999, an array of 17 sonobuoys was deployed in the Bay of Fundy to acquire right whale sounds for a three hour period. The goal of this study was to investigate the ability to accurately locate right whales based on the sounds they make and to estimate sound source levels and detection distances. These factors are important in configuring a permanent automated tracking system.

Localisation of right whales was made on two general types of sounds, 'gunshots' and tonal sounds. Gunshots are broad band banging noises, possibly made vocally. The frequency of occurrence of gunshot and tonal sounds in this experiment were 0.9 min^{-1} and 0.3 min^{-1} respectively. Locations of 72 gunshot sounds and 27 tonal sounds were determined to within an average area of 4.89 km^2 (±4.80 km^2 SD) and 1.92 km^2 (±2.65 km^2 SD) respectively. Preliminary sound source levels, estimated from propagation loss curves over Scotian Shelf drift and received spectral density, were estimated to be between 142-179 dB *re* 1 $\mu Pa^2/Hz$ @ 1 m. Source level may be dependent on frequency. The source level estimate could be improved with measured propagation loss and more accurate whale locations. The average distance to sounds detected was 9.92 km. The mean signal-to-noise ratio was 13.64 dB (minimum 5 dB) and did not depend on frequency or distance.

Research is ongoing to investigate methods of automatically detecting right whale sounds in order to make the use of a real-time monitoring system possible. This preliminary study is a positive step forward in reducing the chance of further harm or death due to ship collisions or naval exercises and improving the chance of long-term survival for the right whale species.

Laurinolli M.H., Hay A.E. 2001. Locating North Atlantic right whales (Eubalaena glacialis) in the Bay of Fundy using multiple sonobuoys. DREA CR 2001–062 Dalhousie University.

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Sommaire

Ces dernières années, la Marine canadienne s'inquiète de plus en plus des répercussions possibles des exercices navals, notamment le sonar actif de basse fréquence (LFA) ou les déplacements maritimes, dans ou à proximité d'habitats fragiles d'espèces de baleine menacées d'extinction. Une façon de minimiser l'impact est de déterminer en tout temps la position des baleines pendant de tels exercices.

Pour atteindre cet objectif, on suggère, entre autres, de se servir des sons émis par les baleines pour les localiser automatiquement par ordinateur, en temps réel. Cette information peut alors être transmise aux bateaux pour les prévenir de la présence de baleines dans le secteur. Le 29 juillet 1999, un réseau de 17 bouées acoustiques était déployé dans la baie de Fundy pour obtenir des sons de baleines noires pendant une période de trois heures. Le but de cette étude était d'examiner la capacité de localisation avec exactitude des baleines d'après les sons qu'elles émettent, et d'estimer les niveaux d'émission des sons et les distances de détection. Ces facteurs sont importants pour la configuration d'un système de repérage automatisé permanent.

La localisation des baleines noires était effectuée d'après deux types de sons courants: des sons tonals et des «coups isolés». Ces derniers sont des claquements large bande, possiblement vocaux. Les fréquences auxquels se produisaient les sons tonals et les coups isolés dans cette expérience étaient, respectivement, de 0,9 min^{-1}. et de 0,3 min^{-1}. Les positions de 72 coups isolés et de 27 sons tonals ont été identifiées respectivement à 4,89 km^2 près (écart-type ±4,80 km^2) et à 1,92 km^2 près (écart-type ±2,65 km^2). Des niveaux préliminaires d'émission des sons, calculés à partir des courbes de perte de propagation sur les dépôts glaciaires de la plate-forme néo-écossaise et de la densité spectrale recueillie, étaient estimés de 142 à 179 dB *re* 1 $\mu Pa^2/Hz$ @ 1 m. Le niveau d'émission peut être lié à la fréquence. L'estimation du niveau d'émission pourrait être améliorée par la mesure de la perte de propagation et par une détermination plus exacte de la position des baleines. La distance moyenne aux sons détectés étaient de 9,92 km. Le rapport signal/bruit moyen était de 13,64 dB (minimum de 5 dB) et n'était lié ni à la fréquence ni à la distance.

Des recherches sont en cours pour examiner des méthodes de repérage automatique des sons émis par les baleines noires afin de rendre possible l'utilisation d'un système de surveillance en temps réel. Cette étude préliminaire est un pas dans la bonne direction pour réduire le risque de dommages supplémentaires et de mort résultant de collisions avec des bateaux ou d'exercices navals, et pour augmenter à long terme les chances de survie de la baleine noire.

Laurinolli M.H., Hay A.E. 2001. Locating North Atlantic right whales (Eubalaena glacialis) in the Bay of Fundy using multiple sonobuoys. DREA CR 2001–062 Dalhousie University

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1 Introduction

The North Atlantic right whale (*Eubalaena glacialis*) experienced such extremely high whaling rates in the 1500's to the early 1900's that they were almost completely exterminated (Brownell Jr. *et al.*, 1986). They have been protected from whaling since 1935, but still only number less than 350 in the North Atlantic (Knowlton *et al.*, 1992) and are considered to be the most endangered large cetacean in the world (Caswell *et al.*, 1999; Aguilar, 1986). This whale population is estimated to be declining by 2.4 % per year, indicating that it could become extinct within 200 years (Caswell *et al.*, 1999). Between 1970 and 1998, at least 35 % (15 of 43) of known right whale deaths were due to ship collisions (Laist *et al.*, 2001) and another 5 % were due to entanglement in fishing gear (Kraus, 1997; Kenney and Kraus, 1993). Three of these collision deaths occurred in the Bay of Fundy in 1992, 1995, and 1997 (Anonymous, 1999). It is clear that the most effective way to improve the chance of long-term survival of North Atlantic right whales is to reduce human-caused mortality (Caswell *et al.*, 1999; Kraus, 1990). Existing measures for preventing ship-strikes include aerial and vessel surveys, but visibility, weather conditions, and cost limit their utility.

It has been suggested by the Dalhousie University/Defence Research Establishment Atlantic right whale research group that a passive acoustic real-time monitoring system could be used to determine right whale locations in the Bay of Fundy. The Bay is a critical, yet dangerous, habitat for North Atlantic right whales due to overlap of prime habitat and busy shipping lanes. The proximity of the habitat to land suggests that placement of a tracking system is logistically feasible.

Clark (1980), Cummings and Holliday (1985), and McDonald *et al.* (1995) have

demonstrated the ability to locate whales using hydrophone arrays. Although Clark (1980) located southern right whales using three hydrophones, there has not yet been a study like this on North Atlantic right whales. Preliminary studies have suggested that North Atlantic and southern right whales may make similar sounds but this is still inconclusive (Matthews *et al.*, 2000). A few studies have looked at the methods of automatically detecting whale sounds such as neural nets and cross-correlation techniques (Potter, 1993; Chiu *et al.*, 1999). These techniques have been suggested to be useful for carrying out whale censuses from pre-recorded data but a workable scheme to detect whales in real time is yet to be accomplished. These studies suggest that real-time automated whale localisation should be feasible although not simple.

A pilot study was undertaken in the Bay of Fundy by the Defence Research Establishment Atlantic (DREA) and Dalhousie University on July 29, 1999 to collect acoustic data using a sonobuoy array for the purpose of right whale sound detection and localisation.

The main objective of this study is to use right whale acoustic data from the sonobuoy array to spatially locate right whales through their sounds in the Bay of Fundy. Secondary objectives include determination of source levels and detection distances.

2 Methods

2.1 Sound Speed Determination

A historical record spanning approximately the last 90 years of hydrographic data for the Bay of Fundy was used to calculate typical sound speed profiles. The average surface sound

speed for July and August rounded to the nearest 10 ms^{-1} was 1490 ms^{-1} (Fig. 1). This sound speed was used for localisations.

2.2 Data Acquisition

On July 29, 1999, the 415 Maritime Patrol "Swordfish" Squadron, CFB Greenwood and DREA deployed 17 sonobuoys in Grand Manan Basin in the Bay of Fundy. The sonobuoys used were of type SSQ-57B (x6), SSQ-53D (x5), SSQ-53E (x3), and SSQ-525A (x3). The sonobuoys were dropped in a 160 km^2 triangular pattern of 6 stations with groups of 2-3 sonobuoys at each apex and at the midpoints of the sides of the triangle. Each station was designated as B1-B8 (Fig. 2). Single sonobuoys were deployed at B7 and B8 in the proximity of right whales sighted from the New England Aquarium research vessel *Neirid*. A radio frequency (RF) signal tracker on the aircraft was used to located the sonobuoys to 100 m accuracy. The position accuracy of sonobuoys relative to each other should be less than 100 m. Positions for all sonobuoys were not available. Figure 2 shows the start positions of sonobuoys that were tracked. The other positions were extrapolated from these. The stations at which they were dropped are listed in Table 1.

Data were transmitted by radio to the aircraft and written on a 28-track magnetic tape using the onboard analog tape recorder. These were played back at DREA, passed through anti-aliasing filters with a cut-off frequency of 3277 Hz, digitized at a sampling frequency of 6554 Hz, and stored onto digital linear tapes (DLT). Approximately three hours of data were recorded onto two tapes between 1300-1600 UTC (Coordinated Universal Time). Each sonobuoy had a recording range between 10 Hz to 2.4 kHz. The 57B

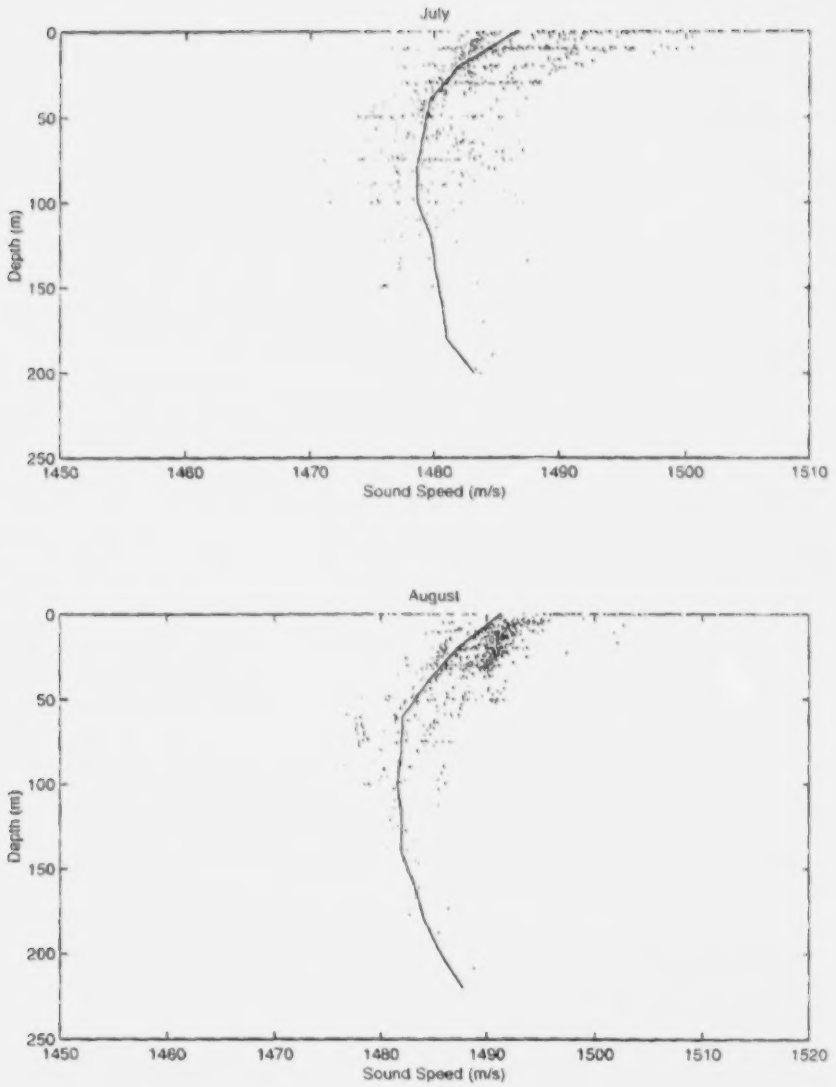

Figure 1: Sound speed profiles from historical data in the Bay of Fundy (latitude 43.3-45.47 degrees north; longitude 65.6-67.5 degrees west) for July and August.

sonobuoys acquired data up to 40 kHz. Each sonobuoy transmitted three data signals, the first being omnidirectional for all sonobuoys and the second and third being directional sine and cosine channels for 53D and 53E type sonobuoys and blank for 57B and 525A type sonobuoys. Each sonobuoy will be designated as 'ch01' to 'ch16' in this report ('ch' referring to channel). The sonobuoy designated as 'ch09a' at location B5 became unserviceable 30 minutes after deployment and was replaced by 'ch09b' giving a total of 48 channels of data on the DLT (some blank if not directional). A 49th channel was assigned for the sonobuoy positions. The resulting data were downloaded using a DREA VMS based AXP mainframe computer. Five-minute Sun audio files were created using IDL5.3 (Interactive Data Language from Research Systems Inc.) on a MacIntosh computer.

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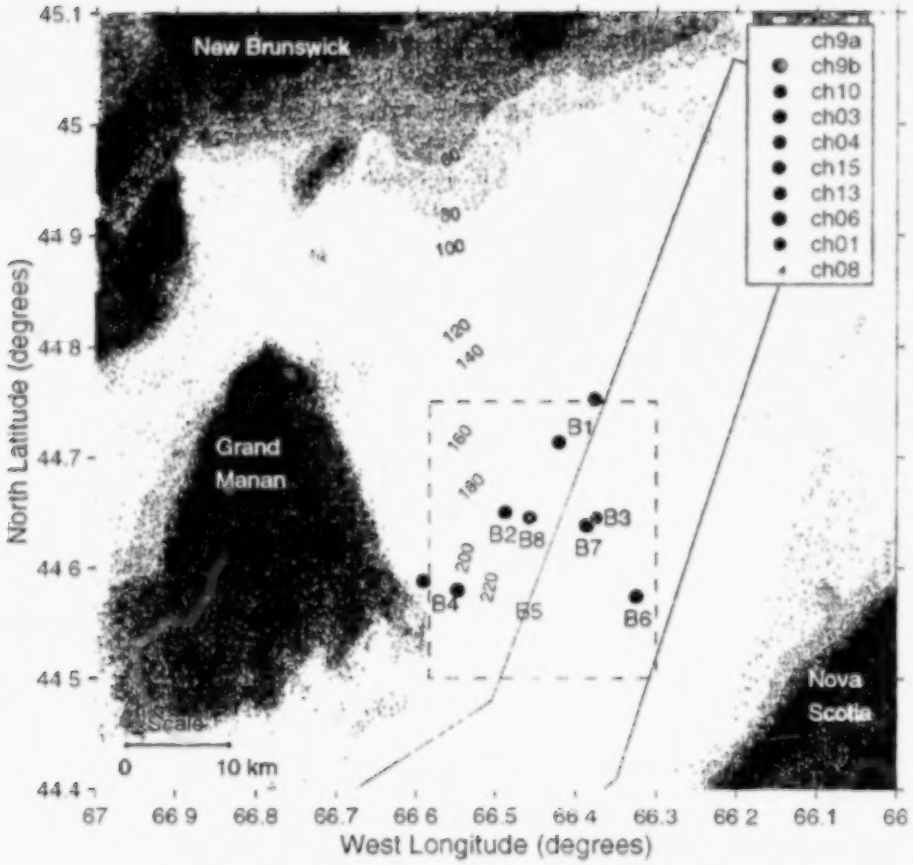

Figure 2: Bathymetric chart (20 m contour intervals) of drop locations (B1 to B8) and tracking for colour-coded sonobuoys and their associated recording channel designations (ch01 to ch16) in the Grand Manan Basin of the Bay of Fundy on 29 July, 1999.

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2.3 Data Analysis

2.3.1 Aural Detection

The audio files from the omnidirectional channels of all 17 sonobuoys (16 channels on the DLT) were aurally analysed for the presence of right whale sounds. These sounds were determined to have been produced by right whales through analyses made by Vanderlaan *et al.* (2000a) and Clark (1983). The time of each whale sound was recorded in seconds from the start of the five-minute file. Notes were made as to whether the sounds seemed 'low' or 'high' in frequency and if they were 'upsweeping' or 'downsweeping' in frequency. The spectrograms of each 'whale sound' were viewed using CoolEdit2000 to verify the sound structure and determine if harmonic frequencies were detectable. The sounds were tabulated and a distinction was made between strong and weak sounds. Twelve-second spectrograms were created using MATLAB5 starting approximately two seconds before each sound. The spectrograms had a frequency resolution of 5 Hz and time resolution of 6 ms.

An initial subjective analysis was made of the approximate sound arrival times on the different sonobuoys to determine which ones may have been the same sound recorded at different locations. The maximum time difference possible was approximated from the distance between the sonobuoys and a sound speed of 1490 ms^{-1}. Generally, the maximum time between sounds selected was not more than five seconds even though it could be up to 12 seconds for some sonobuoy pairs.

2.3.2 Localisation

Once the list of sounds for possible localisation was made, one of the stronger sounds in each grouping was selected to be the one to which the others would be correlated. Using MATLAB5, a time and frequency span was visually and manually selected from the spectrogram and a linear cross-correlation was run on the corresponding spectrogram signals on the other sonobuoys. The cross-correlation calculation for each pair of spectrograms followed

$$R = \frac{\Sigma(X - \overline{X})(Y - \overline{Y})}{\sqrt{\Sigma(X - \overline{X})^2 \Sigma(Y - \overline{Y})^2}},$$

where X is the $\log_{10}$ spectral density of one signal as a function of time and frequency and Y is the $\log_{10}$ spectral density of the other signal. The peak cross-correlation values provided precise arrival-time-differences for the sounds. From each time difference between pairs of sonobuoys a hyperbola of equal time difference was calculated. Sounds detected were assumed to have travelled by direct path. The center of the area bounded by the intersecting hyperbolae was taken as the location of the whale. The error in the location was estimated by the area of the polygon bounded by the hyperbolae.

3 Results

3.1 Data Acquisition

Ten of the 17 sonobuoys were successfully tracked during the experiment, although 'ch01' only for the first hour (Fig. 3). Some tracking data were removed ('ch12'and 'ch14') because they did not appear to follow the same advection pattern as the other buoys when

plotted as Longitude (Fig. 4) or Latitude (Fig. 5) against time. The referencing system was likely not working properly for these sonobuoys. The drift of sonobuoy 'ch16' for the last hour of data recording was extrapolated from the end position of 'ch09a' and the drift pattern of 'ch09b', which was the closest to 'ch16'. This was required in order to target sounds that were recorded at station B5 during the last hour. The positions for the un-tracked sonobuoys were assumed to be the same as for one of the other sonobuoys dropped at the same location. The tracking for 'ch02' and 'ch14' was assumed to be the same as for 'ch10'; that of 'ch12' and the last two hours of 'ch01' equal to 'ch03'; 'ch05' equal to 'ch13'; and 'ch11' equal to 'ch06'.

The tracking and data acquisition times in UTC are given in Table 1. However, not all this time contained usable data. The total data time including all sonobuoys was 25 h 24 m out of the 38 h 58 m acquired (Table 2). Sonobuoys 'ch02', 'ch13', and 'ch15' were unserviceable and therefore had no data. About 30-60 min of data time were recorded on sonobouys 'ch04', 'ch09a', 'ch09b', and 'ch14'. Sonobuoy 'ch12' had about 80 min of data and the others had about 2-2.5 hours.

3.2 The Sounds

The sounds of the right whales were generally of five different types (Fig. 6). These were grouped into the two general categories of 'gunshots' and tonal sounds. The tonal sound category also included pulsive or raspy sounds that would not generally be classified as tonal. The sounds in the tonal group were characterised as being 'moans' or 'groans', 'downsweeping cries', low frequency 'upsweeps', and 'trumpets'. Some of the 'groans'

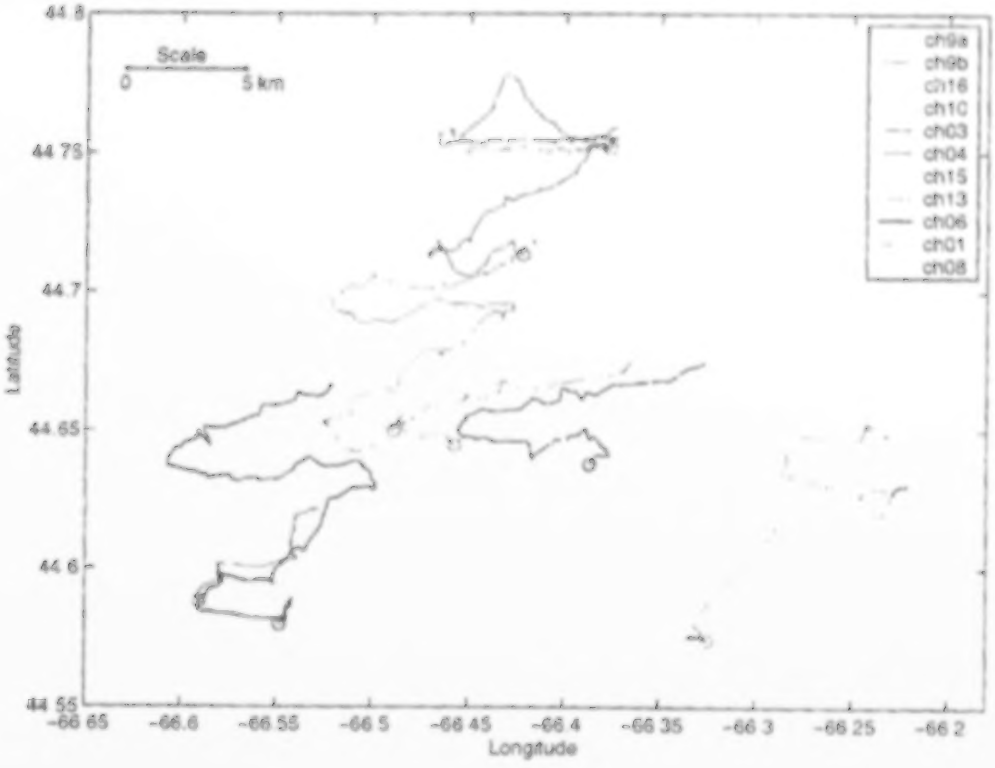

Figure 3: Sonobuoy drift during deployment in the Bay of Fundy on 29 July, 1999. The drift of sonobuoy 'ch16' was extrapolated from the end position of 'ch09a' and the pattern of 'ch09b'.

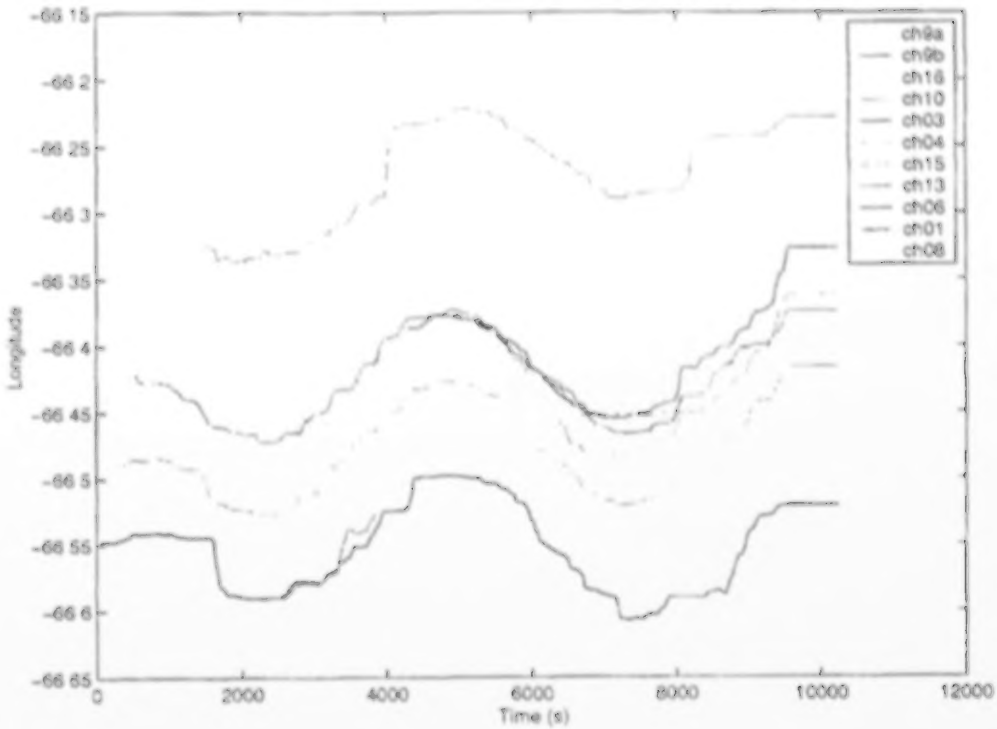

Figure 4: Sonobuoy drift in longitude over time during deployment. The drift of sonobuoy 'ch16' was extrapolated from the end position of 'ch09a' and the pattern of 'ch09b'.

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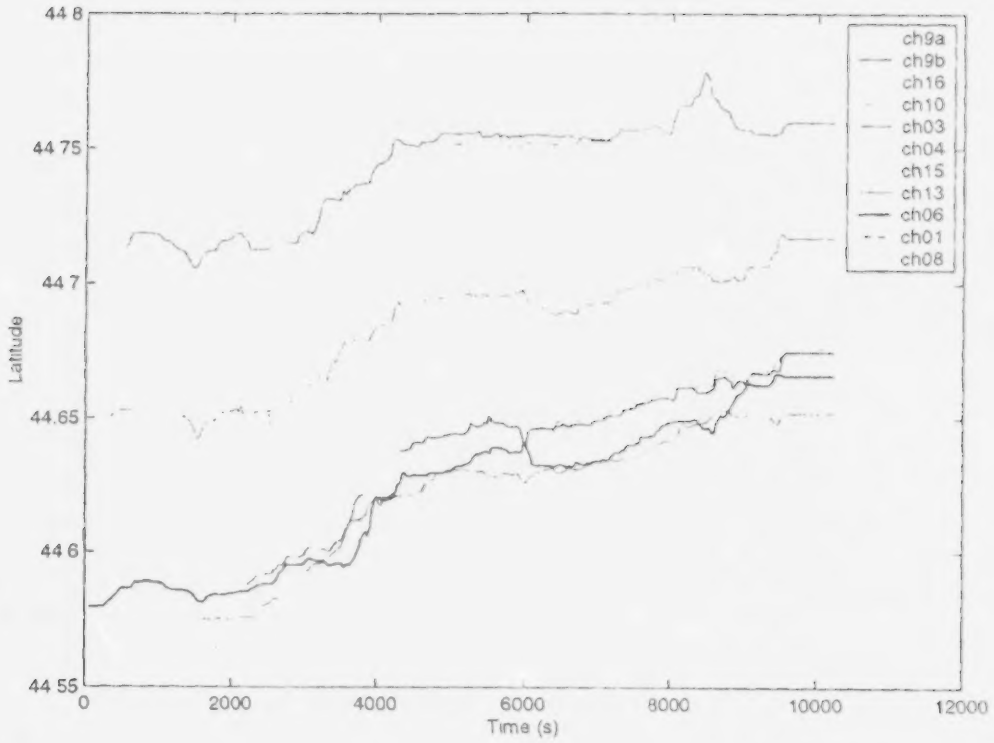

Figure 5: Sonobuoy drift in latitude over time during deployment. The drift of sonobuoy 'ch16' was extrapolated from the end position of 'ch09a' and the pattern of 'ch09b'.

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Table 1: Position tracking time and data recording time for sonobuoys.

STATION	BUOY	TRACKING START	TRACKING END	RECORDING START	RECORDING END
B1	ch01	14:29:49	15:25:57	13:15:10	15:58:40
B1	ch03	13:15:45	15:58:05	13.15:32	15:58:40
B1	ch12	13:18:40	14.25:56	13:18:33	15:58:40
B2	ch05	N/A	N/A	13:12:29	15:58:40
B2	ch13	13:12:50	15:58:05	13:12:50	15:58.40
B3	ch07	N/A	N/A	13:20:14	15:58:40
B3	ch08	13:21:07	15.58:05	13:21.08	15:58:40
B4	ch04	13:43:31	15:58:05	13:10:49	15:58:40
B4	ch06	13:08:35	15:58:05	13:08.31	15:58 40
B4	ch11	N/A	N/A	13:10:36	15:58:40
B5	ch09a	13:34:24	14:12:43	14:19:35	14:50:23
B5	ch16	N/A	N/A	13:34:16	15:58:40
B6	ch02	N/A	N/A	13:26:22	15:58 40
B6	ch10	13:32:29	15:58:05	13:32.56	15.58.40
B6	ch14	13:27:00	14:29:21	13:27:00	15:58:40
B7	ch09b	14:19:02	15:58:05	14:54:22	15:58 40
B8	ch15	14:53:58	15:58:05	14:50:19	15:58.40

Table 2: Total time recorded and usable data time on sonobuoys.

BUOY	RECORDED (H:MM:SS)	DATA TIME (H:MM:SS)
ch01	2:39:31	2:26:50
ch02	2:28:19	0:00:00
ch03	2:39:09	2:24:31
ch04	2:43:52	0:28:55
ch05	2:42:52	2:24:37
ch06	2:46:10	2:33:43
ch07	2:34:27	1:58:15
ch08	2:33:33	2:28:34
ch09a	0:30:48	0:30:48
ch09b	1:04:18	1:03:38
ch10	2:21:45	2:19:21
ch11	2:44:05	2:29:57
ch12	2:36:08	1:18:34
ch13	2:41:51	0:00:00
ch14	2:27:41	0:53:25
ch15	1:04:22	0.00:46
ch16	2:20:25	2:02:19
Total	38:58:36	25:24:13

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and 'trumpets' sounded raspy and could be considered pulsive (see Fig. 6(c)). The moans were generally of longer duration than other sounds at up to 2 s. The other sounds were closer to 0.5-1.5 s long, except for the 'gunshots' which were broadband banging sounds of about 0.2 s (see Fig. 6(f)). Many vocalisations, especially those called 'cries' were made up of several harmonic frequencies (see Fig. 6(e)).

Of the total of 255 tonal sounds audible in the recordings, 217 were considered loud enough to be visible on a spectrogram. A total of 1408 gunshots were audible, of which 727 were considered to be visible in the spectrogram. Taking into account only the stronger sounds, the frequency of tonal sounds was 0.3 min^{-1} and that of gunshots was 0.9 min^{-1}. There were 3 times more tonal sounds during the last hour of recording (1500-1600 UTC) than during the first two hours and 1.4 times more gunshots during the first hour.

3.3 Localisation

Locations were obtained for 27 tonal sounds (calls) and 72 gunshot sounds (Fig. 7). The majority of the targets were located northeast of the visual sightings made of right whales on the day of the experiment. The sounds were also predominantly in the shipping lane. The sonobuoys used most often for localising tonal sounds were 'ch09a', 'ch09b', 'ch16', 'ch05', and 'ch12'. Sonobuoys 'ch06' and 'ch11' were also used for some sounds. Figure 8 gives an example of the spectrogram cross-correlation of an upsweeping vocalisation from four sonobuoys. In some cases, the higher harmonics were of greater intensity and more useful for cross-correlation. The R-values were 0.35-0.49 corresponding to distinct peaks visible on the cross-correlation plots (see Fig. 8(c,e,g)). Localisation of this sound is

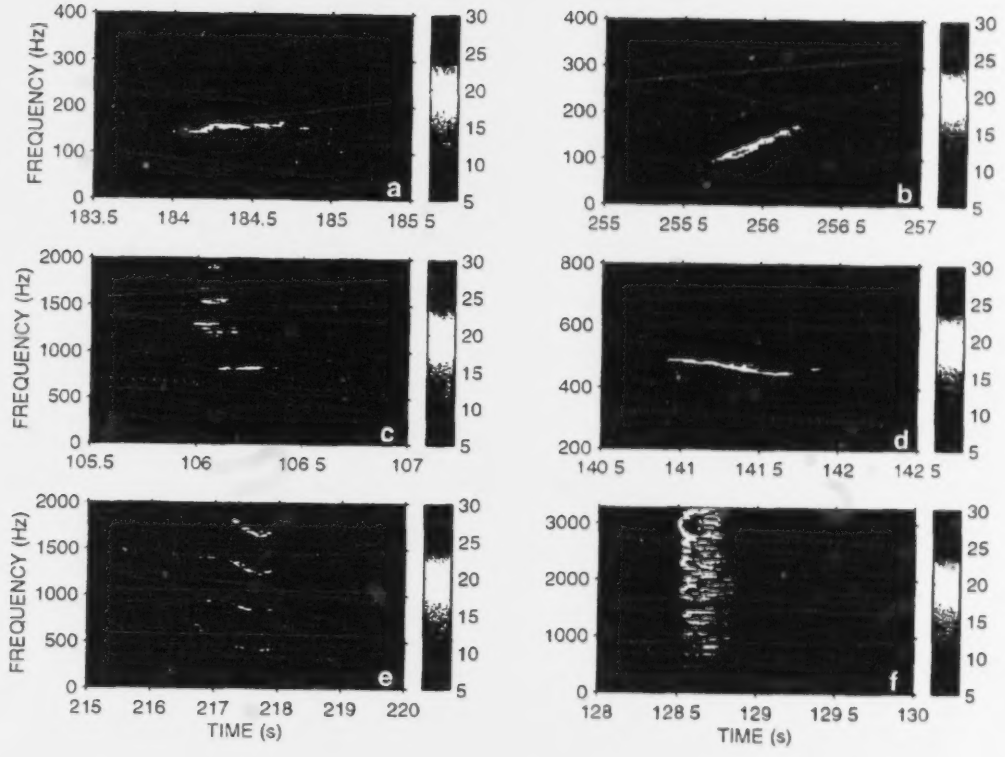

Figure 6: Sample spectrograms (colorbar is signal-to-noise in dB) of right whale sounds recorded in the Bay of Fundy on July 29,1999. A 'moan' is represented in (a); a 'low upsweep' in (b); a 'trumpet' in (c); a 'down cry' in (d); a 'cry' with harmonics in (e); and a 'gunshot' in (f).

shown in Fig. 9. The area of the polygon bounded by each combination of three hyperbolae is 1.6 km^2. The whale was likely within this polygon.

The majority of the gunshot sounds were detected on sonobuoys 'ch09a', 'ch09b', 'ch16', 'ch05', 'ch12','ch07', 'ch08', 'ch01', 'ch03', 'ch10', and 'ch14'. Some gunshots were also targeted with sonobuoys 'ch06' and 'ch11'. A cross-correlation and targeting of a gunshot is shown in Figure 10 and Figure 11 respectively. The cross-correlation R-values in this example varied from 0.17-0.31. Although these values are low, the spectrograms and strong peaks in the cross-correlation plots suggest a good match. Each cross-correlation plot in Figure 10 has a relatively high second peak about one second later suggesting that the correct gunshot was chosen for localisation. The area of the polygon bounded by the hyperbolae of localisation is 3.2 km^2.

A single point location generally was not obtained in any localisation. If only three sonobuoys were used for the localisation, all three hyperbolae intersected at a single point since the three time differences are not independent of each other, but no error estimate could be made. For the tonal sounds, the average polygon area was 1.92 km^2 for targets detected on four or more sonobuoys (N=11; SD=2.65 km^2; max=8.39 km^2; min=0.026 km^2). The average polygon area for gunshot sounds was 4.89 km^2 (N=50; SD=4.80 km^2; max=19.86 km^2; min=0.0014 km^2).

3.4 Source Levels

An estimate was made of North Atlantic right whale sound source levels using the propagation loss curves presented in Desharnais *et al.* (2000). Received spectral density levels

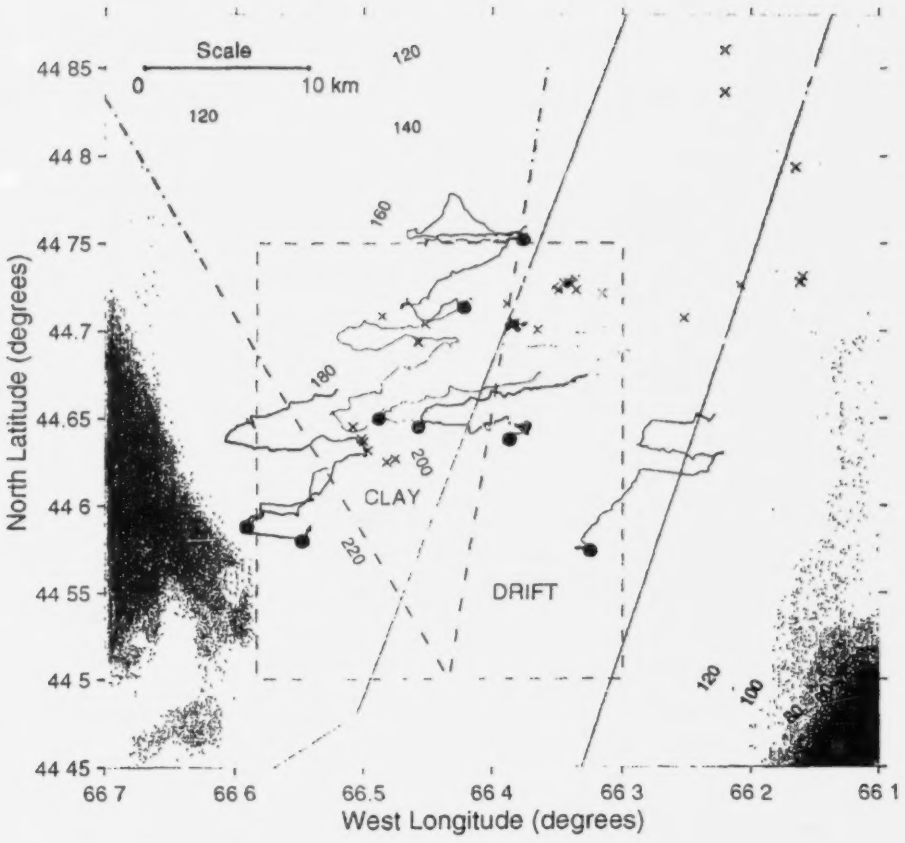

Figure 7: Whale locations determined from the sonobuoy array in the Bay of Fundy on 29 July, 1999. Red crosses indicate whales located from tonal sounds, yellow crosses indicate gunshot sounds, and blue crosses indicate whales sighted from the New England Aquarium research vessel *Neirid* on the day of the experiment. The solid lines indicate the boundary of the shipping lane, the dashed line outlines the right whale conservation area, and the dash-dot line identifies the approximate upper sediment type boundary (La Have clay vs. Scotian Shelf drift). The sonobuoy drift patterns are also shown corresponding to the same color scheme as in Fig. 3.

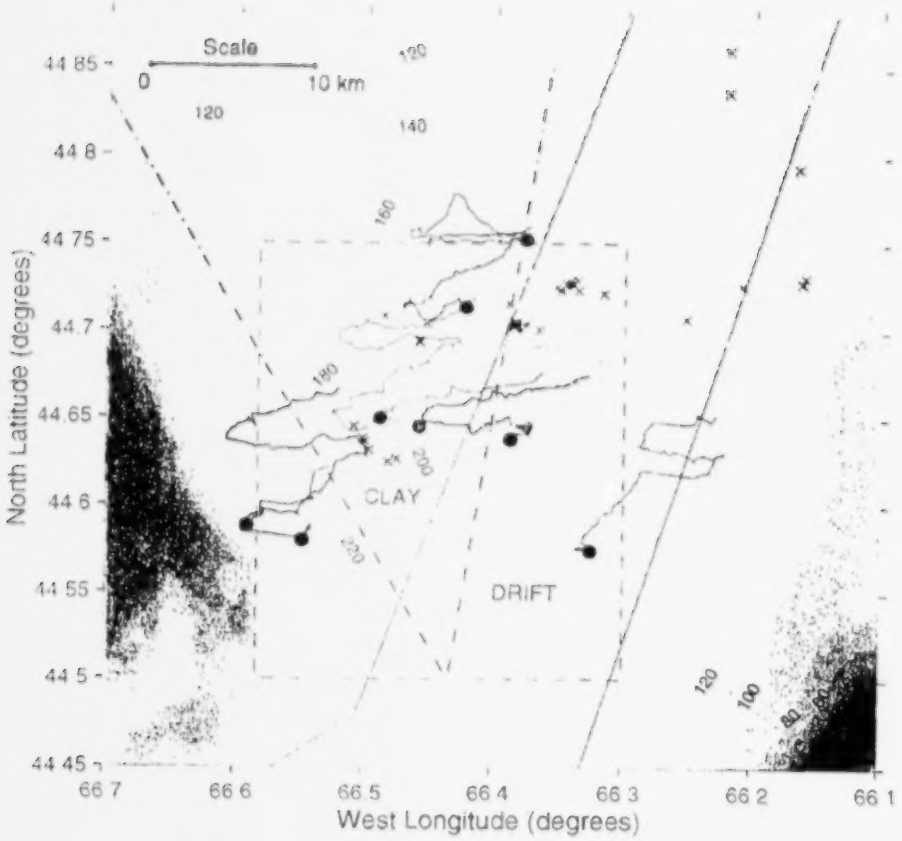

Figure 7: Whale locations determined from the sonobuoy array in the Bay of Fundy on 29 July, 1999. Red crosses indicate whales located from tonal sounds, yellow crosses indicate gunshot sounds, and blue crosses indicate whales sighted from the New England Aquarium research vessel *Nefrid* on the day of the experiment. The solid lines indicate the boundary of the shipping lane, the dashed line outlines the right whale conservation area, and the dash dot line identifies the approximate upper sediment type boundary (La Have clay vs. Scotian Shelf drift). The sonobuoy drift patterns are also shown corresponding to the same color scheme as in Fig. 3.

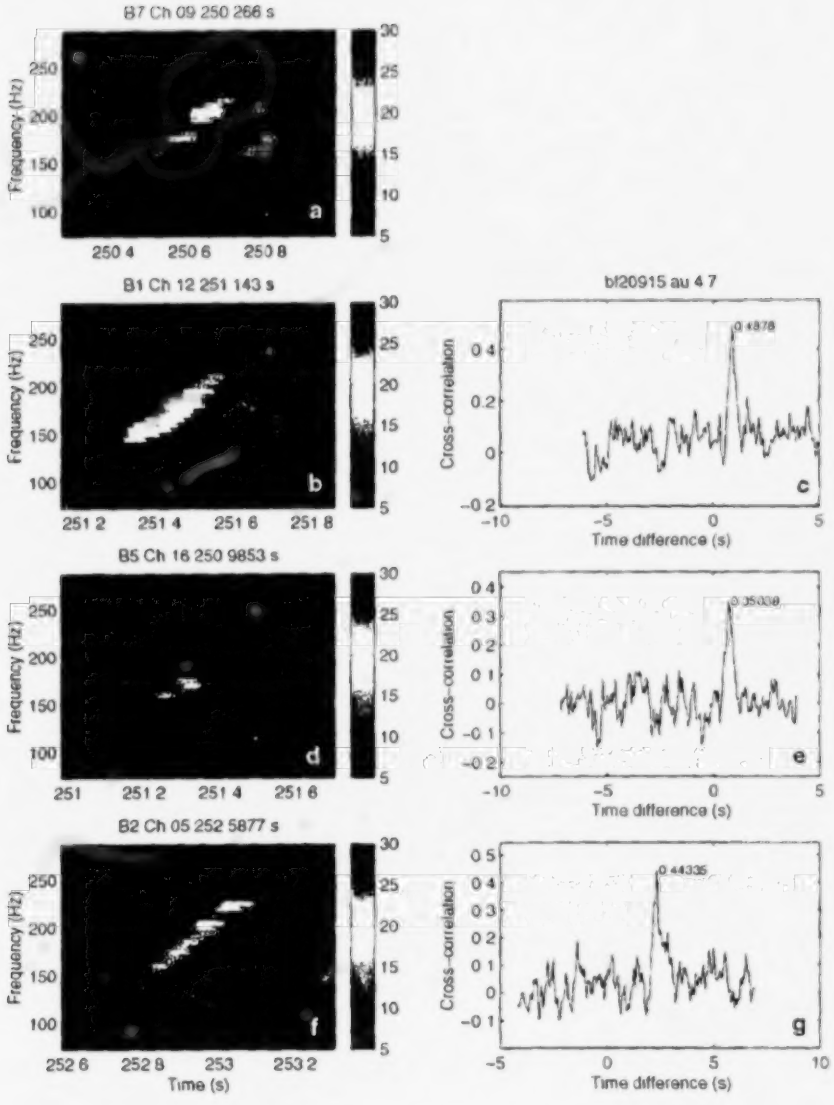

Figure 8: Spectrograms and cross-correlation plots (to the right of the corresponding spectrogram) of a right whale vocalisation detected on four sonobuoys. Arrival times are given at the top of each spectrogram. Cross-correlation R-values are given next to the highest peak in plots (c), (e), and (g).

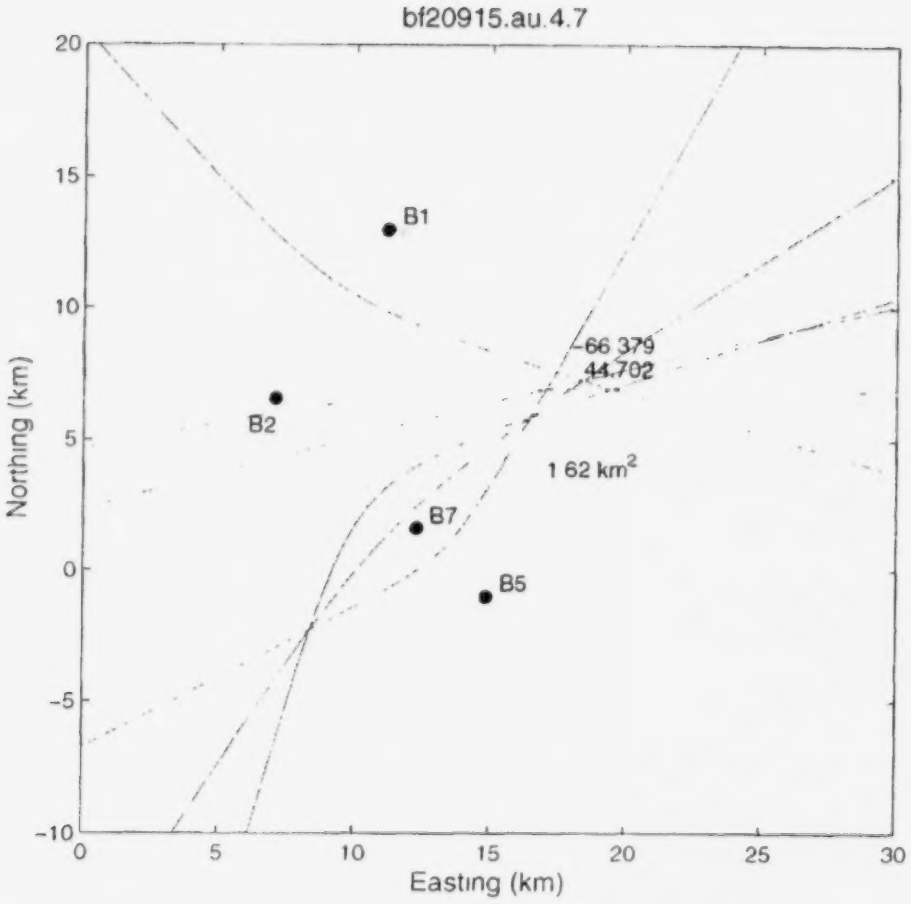

Figure 9: Localisation of a right whale vocalisation using hyperbolae of equal time difference. The area of the polygon bounded by intersections of three hyperbolae is 1.62 km^2.

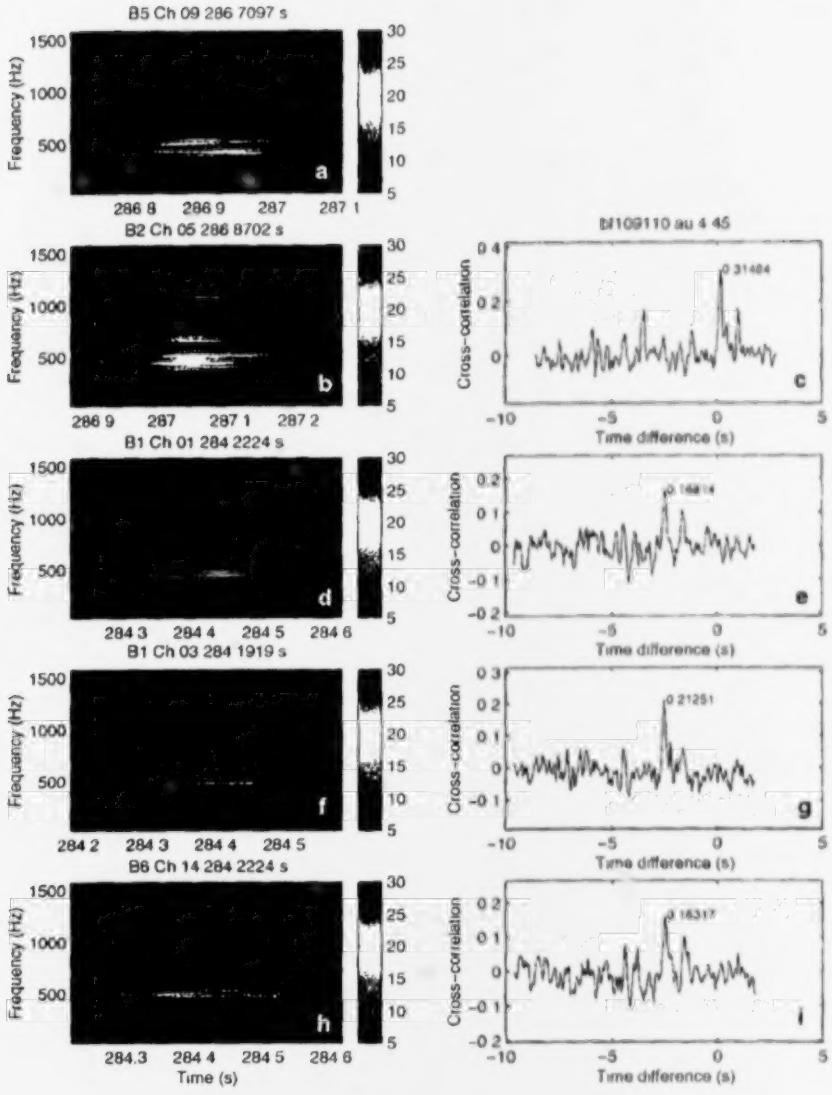

Figure 10: Spectrograms and cross-correlation plots (to the right of the corresponding spectrogram) of a right whale vocalisation detected on four sonobuoys. Arrival times are given at the top of each spectrogram. Cross-correlation R-values are given next to the highest peak in plots (c), (e), (g), and (i).

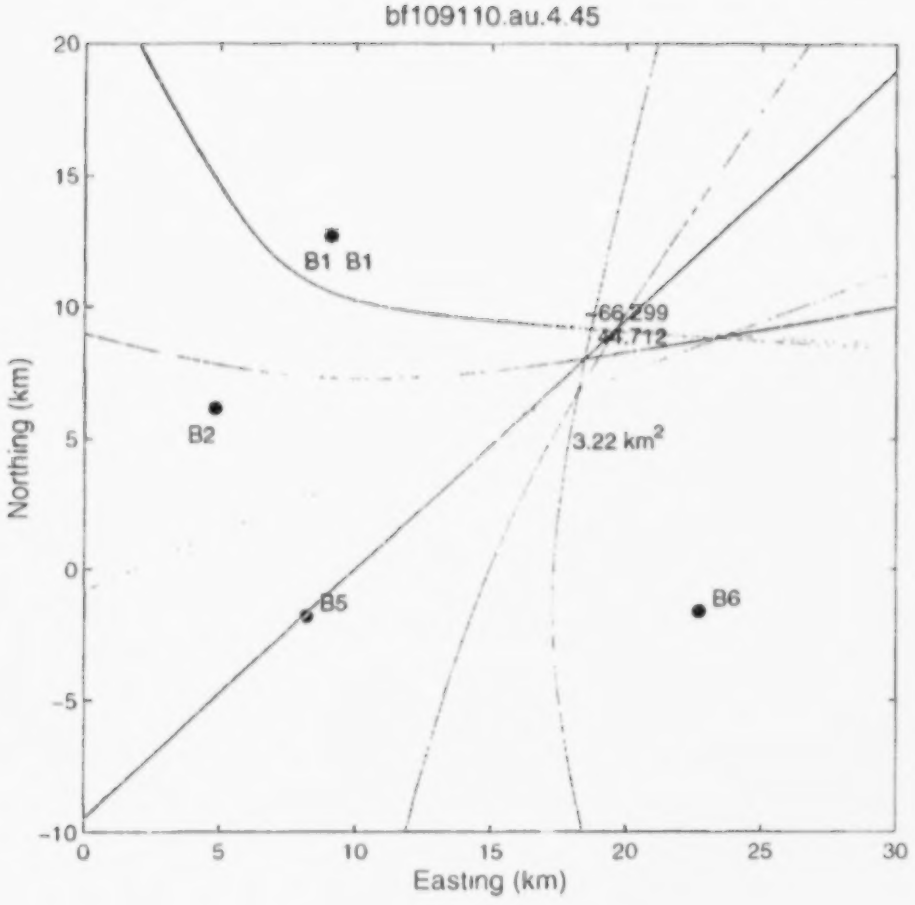

Figure 11: Localisation of a right whale gunshot sound using hyperbolae of equal time difference. The area of the polygon bounded by intersections of each combination of three hyperbolae is 3.22 km^2.

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(RSDL, dB *re* 1 $\mu Pa^2/Hz$) for all tonal and gunshot sounds plotted against distance suggest that source level depends on frequency (Fig. 12). Lower frequency sounds or harmonics had a higher received spectral density than higher frequencies. The mean RSDL and mean distance for each frequency range are given in Table 3. The overall average distance to sounds detected was 9.92 km. Several sounds were detected up to 20 km away from the sonobuoys. Using the propagation loss curve for Scotian Shelf drift, since the majority of whale sounds came from this area (see Fig. 7), and the mean distance and mean RSDL, the source level range would be 142-179 dB *re* 1 $\mu Pa^2/Hz$ @ 1 m. The average signal-to-noise ratio (SNR) for the right whale sounds was 13.64 dB (N=73) and the minimum was as low as 5 dB (Fig. 13). There was no relationship between SNR level and frequency.

Table 3: Mean distance and received sound pressure level (standard deviation in brackets) for frequency ranges 100-200 Hz (N=31), 200-800 Hz (N=13), and 800-2000 Hz (N=29) of right whale sounds localised.

FREQUENCY	DISTANCE (km)	RSDL (dB *re* 1 $\mu Pa^2/Hz$)
100-200	10.48 (5.25)	102.21 (5.58)
200-800	9.56 (4.31)	87.23 (8.24)
800-2000	9.49 (4.64)	74.85 (10.40)

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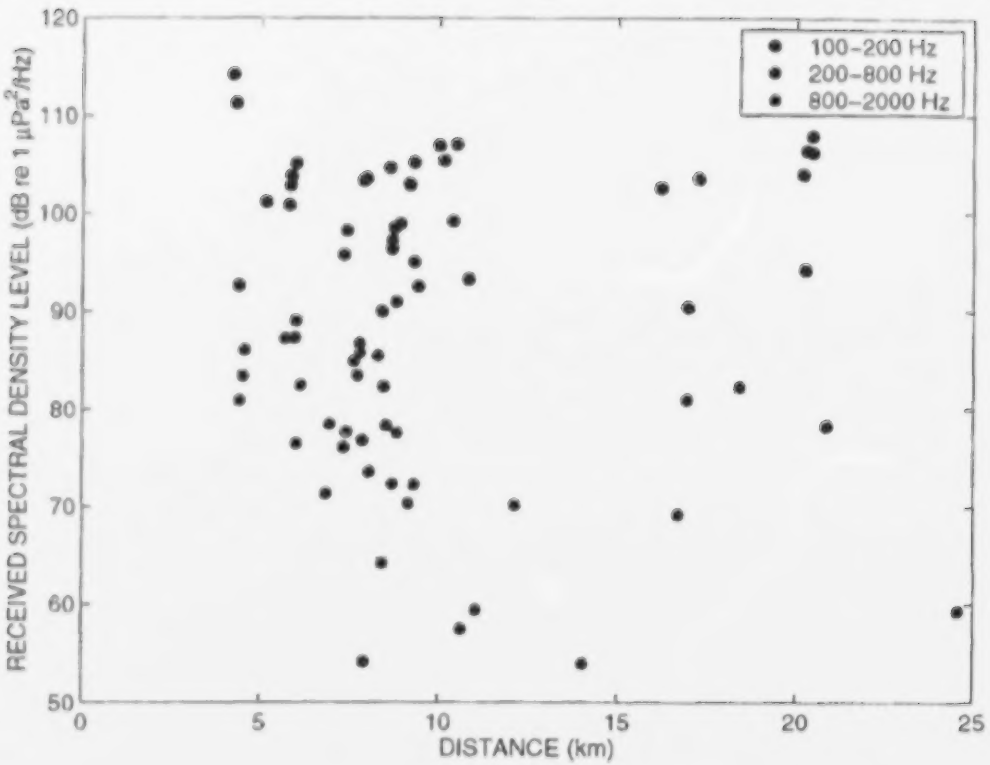

Figure 12: Received spectral density level (dB *re* 1 μPa^2/Hz) against distance (km) to sound for frequency ranges 100-200 Hz (N=31), 200-800 Hz (N=13), and 800-2000 Hz (N=29).

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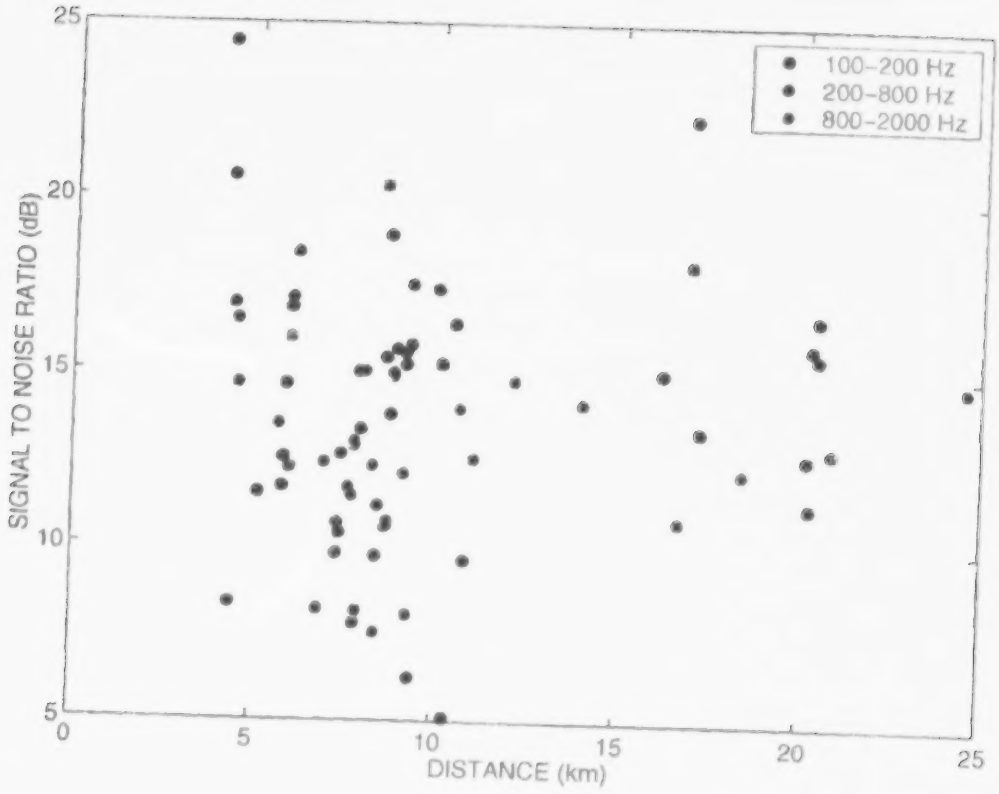

Figure 13: Signal-to-noise ratio (dB) plotted against distance (km) to receiver for frequency ranges 100-200 Hz (N=31), 200-800 Hz (N=13), and 800-2000 Hz (N=29).

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4 Discussion

This study was a good first step in testing the usage of hydrophone arrays for localising North Atlantic right whales. The greatest difficulty in acquiring accurate locations for the whales came from the lack of accurate positioning for all the sonobuoys. Of the 14 sonobuoys with usable data recordings, only 8 were tracked. This resulted in sometimes large 'areas' of localisation rather than a single point location, especially when more than 4 or 5 sonobuoys were used. For the tonal sounds, positions for three of the four sonobuoys with the most sounds had to be extrapolated. The same applies to gunshot sounds although these were heard on more sonobuoys. The 100-m error in sonobuoys that were tracked could change the localisation position by up to 0.5 km. Errors in time estimation are not expected to be greater than 0.05 s (1 % of the average maximum time difference of 5 s). Such a time error would affect the targeting position by 0.5 km. The cross-correlation technique is more accurate than 0.05 s unless there is another similar sound within 5-10 s of the correct sound. This is common with gunshot sounds. A permanent hydrophone array that does not change position would be more effective in accurately localising whales. In some localisations, two ambiguous points were obtained. This usually happened when only three sonobuoys were used. The point that was closest to the other whale locations was arbitrarily chosen to be the correct one. Sound speed changes and propagation loss could also have an effect on localisation. The issue of error generated by targeting in two dimensions rather than three should also be investigated.

The use of sonobuoys which transmit the data by radio waves would not be suggested for a permanent whale tracking system in the Bay of Fundy. Much of the recordings

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(35 %) on the sonobuoys were not usable due to interference by dispatchers on the radio frequencies used, discontinuous recording, or static because of the proximity to land. This greatly reduced the likelihood of detecting the same sound on at least three sonobuoys.

The majority of whale locations acquired were in a west to east band at about latitude 44.7°N and longitude 66.45 to 66.2°W. This area is in the northeast corner of the right whale conservation area and east of this into the shipping lane (see Fig. 7). These locations are consistent with the positions of the sonobuoys during the last hour of deployment which is the time when the most sounds were heard. It is likely that the reason why few whale sounds were heard in the vicinity of whale sightings is that the sonobuoys had drifted too far northeast to detect sounds that far away. The number of whale sightings was also limited by heavy fog conditions and location of the vessel. More than ten vocalisations were detected on all three sonobuoys at station 'B1' at the north end of the array but not at the other stations. These sounds tended to be of higher frequency and potentially could not travel far enough to be detected by the other sonobuoys. Much of the sound may have also been lost into the lossy La Have clay type sediment which is present where whales were sighted. The targets that appear furthest to the east may be in error by several kilometres due to the inaccurate sonobuoy positions since the intersecting hyperbolae become closer to being parallel further away from the sonobuoys.

It is possible that human error in selecting which sounds were the same one on different sonobuoys resulted in sighted whales being missed. This bias may have also resulted in whales not being located within 5 km of a sonobuoy (see Fig.12) since the arrival time difference to other sonobuoys would have been as much as 12 s and the observer may not have selected these as being the same sound. The use of an automated computer algorithm

for selecting the appropriate sounds would improve this problem. The cross-correlation method could have been run on longer time periods of data which may have produced greater arrival time differences and also more whale locations.

5 Conclusion

A permanent array used to track whales in real time in the Bay of Fundy should either be in a fixed location or have another method of data transmission than that used by these sonobuoys. The sonobuoys did demonstrate the ability to detect right whales up to 20 km away which is approximately equivalent to the dimensions of the right whale conservation area. The ability to detect whales in real time is dependent upon the ability to detect their sounds automatically with computer algorithms. The data acquired in this study will be used to continue work on methods of automatic detection. Preliminary algorithms have been written to automatically detect whale sounds based on detection of broadband sound bursts above the background noise. This technique is not sufficient to distinguish between whales and other sounds. The algorithms need to include details of frequency ranges, frequency modulation, and sound duration in order to be useful. Preliminary efforts to achieve this have been provided in Vanderlaan *et al.* (2000b) and more work continues. A more accurate estimate of source levels is also important for determining the optimum array dimensions. To get this estimate, more study is necessary on propagation losses in the Bay of Fundy, especially over the La Have clay sediment. These further studies will be taking place during this coming year.

It should also be noted that the sounds that are being called 'gunshots' in this report

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are of unknown origin, but could be very useful for localisation. They are more frequent and much easier to automatically detect than the other types of standard vocalisation sounds, although difficult to distinguish from one another when multiple gunshots are made. Clark (1983) suggested that these sounds are produced by slapping of body parts on the water surface or slapping between two whales. Other researchers (Parks (2000), *pers. comm.*) have suggested that these sounds are vocally produced since no slapping was seen during production of the sound. In either case, the sound is generated by right whales and can be used for localisation and tracking.

Previous studies have not yet determined the relationship between numbers of vocalisations or gunshots heard and the number of right whales actually present. Some research has suggested that North Atlantic right whales do vocalise often enough for passive acoustic localisation to work (Vanderlaan *et al.*, 2000b; Matthews *et al.*, 2000). The development of a real-time passive acoustic right whale monitoring system could have a substantial impact on the survival of this species. If the whales are spending much of their time within the shipping lanes in the Bay of Fundy, as suggested by our findings, a system that gives advanced warning to ships is crucial to preventing further deaths due to collisions. This technique should, however, be used in conjunction with other whale detection methods.

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In July 1999, a 160 km2 array of 17 sonobuoys was deployed in the Grand Manan Basin area of the Bay of Fundy within the designated North Atlantic right whale conservation area. The objectives of this study were to determine the accuracy of locating right whales based on their sounds; to estimate source levels of these sounds; and to determine sound travel distances. Two general types of sounds were identified, typical tonal vocalisations and broad band 0.2 s duration 'gunshots'. Tonal vocalisations occurred at 0.9 min-1 and their locations were determined to within 1.92 km2 (±2.65 km2 SD) on average. Gunshot type sounds were detected at 0.3 min-1 and determined to within 4.89 km2 (±4.80 km2 SD) on average. Right whale sound source levels were estimated to be 142-179 dB *re* 1 mPa2/Hz @ 1 m. Source levels appeared to be dependent on frequency. The mean distance to sounds detected was 9.92 km. The average signal-to-noise ratio was 13.64 dB, with a minimum of 5 dB. Signal-to-noise did not depend on frequency or distance. Further research is continuing to investigate methods of automatically detecting right whale sounds in order to improve the possibility of implementing a real-time whale tracking system.

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Bay of Fundy
Automated detection